Closed Orbit Distortion from Parasitic Collisions in PEP-II†

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Abstract

The dipole force on the beams caused by the parasitic collisions (PCs) induces closed orbit distortions in the interaction region (IR): "typical" bunches (those far away from the ion-clearing gap), collide center-on-center with a small horizontal crossing angle; "pacman" bunches (those close to the gap) not only collide at an angle, but their centers are displaced as well; and the orbit separation between the beams at the PCs is different from nominal. We evaluate these effects as a function of horizontal tune in first-order approximation. This analysis yields one set of constraints that are absolutely necessary, although far from sufficient, for reliable operation. We conclude that the crossing angle and orbit displacements are small except for tune values very close to the integer (above or below), and that fractional tunes ≳ 0.35 are favored.

1 INTRODUCTION

The PEP-II design [1] calls for head-on collisions with magnetic separation in the horizontal plane. This separation scheme entails unavoidable PCs near the interaction point (IP) whose effects on the beam-beam dynamics have been studied quite extensively [1,2].

In this article we address the orbit distortion caused by the net attractive force between the beams. The main consequences that might be relevant to the beam-beam dynamics are an induced horizontal crossing angle, and a change in the orbit separation at the PCs. If the beams were uniformly populated, the crossing angle would be the same for all bunches. However, the existence of an ion-clearing gap complicates matters a bit: those bunches near the head or the tail of the train (dubbed "pacman bunches") do not experience all PCs and hence their crossing angles are different from those bunches in the middle of the train (dubbed "typical"). Pacman bunches also collide off-center due to the imbalance of the net forces to the right and to the left of the IP. Typical bunches experience only a crossing angle without orbit separation at the IP.

2 CALCULATION

The basic beam parameters and optics of the IR are given in Ref. [1]. There are four parasitic collision points on either side of the IP, and the optics is symmetrical about the IP in this region. The PCs are spaced by 63 cm, which is half the bunch spacing. We assume that the ion-clearing gaps in both beams are of the same length, and that the beams are stored in such a way that gaps "collide" with gaps and beams with beams. In other words, we assume that the bunch at the head of the train in one beam collides at the IP with the bunch at the head of the train in the other beam.

The general expression for the closed orbit distortion X_o and slope X_o' (relative to the nominal orbit) at an observation point o produced by discrete kicks $\Delta X_k'$ are given, to first order in $\Delta X_k'$, by

$$X_o = \frac{\sqrt{\beta_o}}{2\sin\pi\nu}\sum_k \Delta X_k'\sqrt{\beta_k}\cos(\Delta\phi_k - \pi\nu) \tag{1}$$

and

$$X_o' \equiv \frac{dX_o}{ds} = \frac{1}{2\sqrt{\beta_o}\sin\pi\nu}\sum_k \Delta X_k'\sqrt{\beta_k}\big(\sin(\Delta\phi_k - \pi\nu) - \alpha_o'\cos(\Delta\phi_k - \pi\nu)\big) \tag{2}$$

where $\Delta\phi_k$ is the horizontal phase advance of point k relative to o and ν is the horizontal tune. The phase advances $\Delta\phi_k$ must be computed by going from o to k in the same sense around the ring for all k, so that they are always ≥ 0. In our case, the kicks $\Delta X_k'$ are produced by the PCs. Each bunch experiences four PCs on either side of the IP, and these PCs are labeled k = –4,...,4, as shown in Fig. 1.

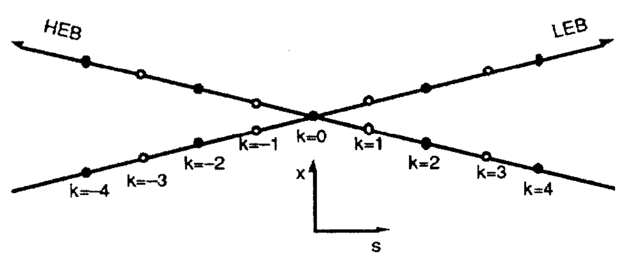

Fig. 1: Plan sketch of the IR showing all four PCs on either side of the IP. Black bunches are shown in their actual position. White bunches show the positions of the PCs when the bunches move by half of a bunch spacing (LEB=low-energy beam, HEB=high-energy beam).

If the horizontal displacement x and azimuthal coordinate s (for both beams) point in the direction as sketched in Fig. 1, then the kicks for $k \geq 1$ are given by

$$\left.\begin{aligned} \text{LEB:}\quad \Delta X_k' &= -\frac{2r_0N_-}{\gamma_+d_k} \\ \text{HEB:}\quad \Delta X_k' &= +\frac{2r_0N_+}{\gamma_-d_k} \end{aligned}\right\} \quad \text{for } k = 1,\cdots,4 \tag{3}$$

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while those for $k \leq -1$ are given by $\Delta X'_{-k} = -\Delta X'_k$ for each beam. The kick at the IP, $\Delta X'_0$, is zero in first approximation for all bunches. Here $r_0 = 2.815 \times 10^{-15}$ m is the classical electron radius, the γ's are the usual relativistic factors, d_k is the orbit separation at the k-th PC, and the N's are the numbers of particles per bunch. The subscripts $\pm$ label the positron or electron beam. If the observation point is the IP, the relative phase advances are

$$\Delta\phi_k = \begin{cases} 2\pi\Delta\nu_k, & k = 1,\cdots,4 \\ 2\pi(\nu - \Delta\nu_{-k}), & k = -4,\cdots,-1 \end{cases} \tag{4}$$

where the $\Delta\nu$'s are the usual phase advances. For other observation points (e.g., at a PC location), some of these phase advances may have to be shifted by $2\pi\nu$. Whatever the observation point is, the phase advance $\Delta\phi_o$ is given by

$$\Delta\phi_o = \begin{cases} 0, & s = o_- \\ 2\pi\nu, & s = o_+ \end{cases} \tag{5}$$

3 RESULTS

We have computed the orbit distortions and slopes for typical and pacman bunches at the IP and at all four PCs [3]. Here we present only the salient results. The PEP-II design calls for a train of 1658 bunches followed by an ion-clearing gap of length equivalent to 88 bunches. Since each bunch could, in principle, experience a collision at the IP plus four PCs on either side of the IP, there are four pacman bunches at the head of the train and four at the tail. We label the head pacman bunches 1, 2, 3 and 4, where #1 is first one. Pacman bunch #1 of the LEB experiences collisions k = 0, 1, 2, 3 and 4, where 0 is the main collision at the IP; bunch #2 experiences collisions k = −1, 0, 1, 2, 3 and 4, etc. The remaining 1650 (typical) bunches experience all nine collisions, namely k = −4, ... , 4.

3.1 Results for typical bunches.

The orbit distortion, Eq. (1), is a periodic function of ν with period 1, so that only the fractional part of the tune matters in this approximation. It is also easily seen from Eqs. (1–5) and the symmetry of the IR optics that the orbit distortions at PCs to the left of the IP (k = −1, ... , −4) are of the same magnitude and opposite sign as those to the right of the IP. Similarly, the orbit distortion of a given tail pacman bunch is of the same magnitude and opposite sign as that for the corresponding head pacman bunch at the same location.

The symmetry of the IR optics implies that typical bunches have $X_o = 0$ and $X'_o \neq 0$, leading to a finite crossing angle, as shown in Fig. 2.

3.2 Results for pacman bunches.

Figure 3 shows the absolute and relative displacements of the orbits of the 1st pacman bunches at the IP. Both bunches are typically displaced to the same side of the nominal orbit because the net imbalance of the forces from the PCs is such that the head bunches of both beams are pulled in the $x < 0$ direction. By symmetry, the last bunches at the tails of the beams are pushed towards $x > 0$ by the same amount as the head bunches are pushed towards $x < 0$. The magnitude of the displacement of the 1st pacman bunch from its nominal orbit is $\lesssim 10$ μm for most values of the tune. More interestingly, the displacement of one bunch relative to the other, which is what matters for the beam-beam dynamics, is $\Delta X < 2$ μm. These numbers are small compared to the rms bunch width of 152 μm.

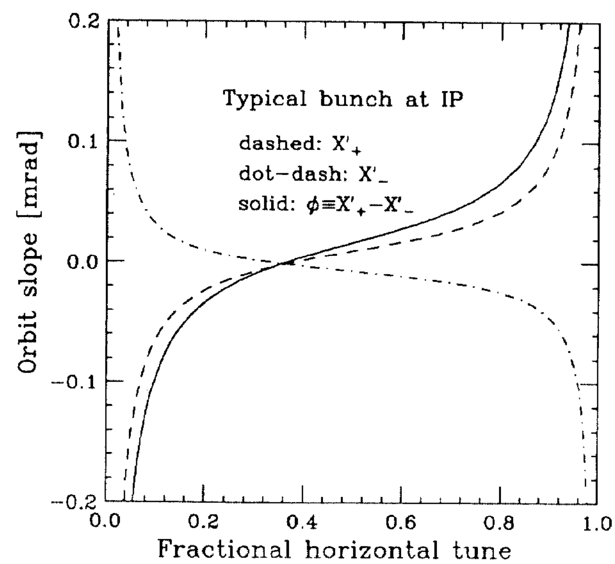

Fig. 2: Horizontal slopes at an LEB point immediately upstream of the IP, and full crossing angle of typical bunches. The crossing angle is computed assuming the same fractional tunes in both beams.

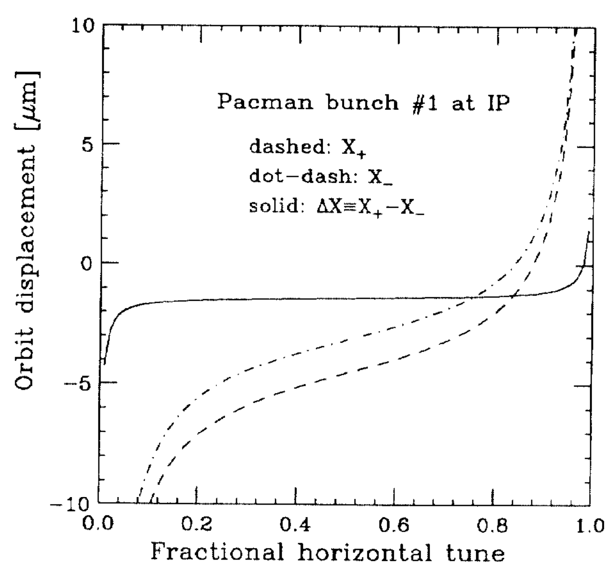

Fig. 3: Orbit distortions of the head pacman bunches at the IP. The change in orbit separation ΔX is computed assuming that the two beams have the same fractional tune.

Figure 4 shows the absolute orbit separation between the two beams at the IP for all four pacman bunches at the head of the train. It is clear that the largest effect is for the 1st pacman bunch (we recall that typical bunches have zero separation at the IP).

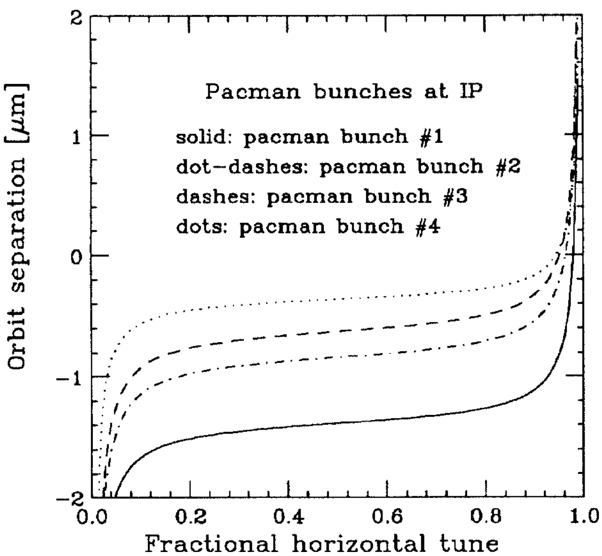

Fig. 4: Beam orbit separation at the IP for all four head pacman bunches.

4 CONCLUSIONS

Unless the tune is very close to an integer value (from below or from above), we conclude that the closed orbit distortion from the PCs is so small for nominal PEP-II parameters that it is expected to have a negligible effect on the dynamics [4,5,6]. The first and last pacman bunches experience the largest orbit separation at the IP. Typical bunches experience a larger shift in orbit separation at the PCs, and a larger crossing angle at the IP, than pacman bunches [3]. More specifically, our results can be summarized as follows:

4.1 Crossing angle.

For fractional horizontal tunes in the range $0.15 \lesssim \nu \lesssim 0.85$, typical bunches collide with a horizontal crossing angle $|\phi| \lesssim 0.1$ mrad, assuming the same fractional tune for the two beams. The 1st pacman bunches collide at a smaller angle, $|\phi| \lesssim 0.05$ mrad, and the other pacman bunches collide at angles in between 0.05 mrad and 0.1 mrad. It is always possible to cancel the crossing angle provided that one beam has fractional tune > 0.35 and the other < 0.35. In any case, the crossing angle is much smaller than the ratio $\sigma_x/\sigma_\ell = 15.6 \times 10^{-3}$, and therefore this crossing angle effect is expected to be negligible [5].

4.2 Orbit separation.

Pacman bunches collide off-center at the IP. The 1st pacman bunches at the head of the trains (and the last pacman bunches at the tail), have the largest orbit displacements. For fractional tunes in the range $0.15 \lesssim \nu \lesssim 0.85$, the bunch centers are displaced from the nominal orbit by $|X_\pm| \lesssim 10\mu$m, which is $\lesssim$ 7% of the rms beam size, $\sigma_x = 152$ μm. Multiparticle simulations for displaced beams [6] suggest that a separation of this magnitude should have a negligible effect on the luminosity performance. Even better, if the two beams have the same, or comparable, fractional tunes, the bunches in the two beams are displaced *to the same side* of the IP, so that their centers are displaced from each other by an even smaller amount, $|\Delta X| < 2$ μm, which is negligible. If the beams have substantially different fractional tunes, however, the bunch separation can be significant.

The beam separations of all bunches (typical and pacman) at all PCs are modified from the nominal values. At any given PC the fractional change in orbit separation, $\Delta d/d$, is largest for a typical bunch and smallest for the head pacman bunch. For any given bunch, the effect is largest at the 1st PC and smallest at the 4th PC. The change $\Delta d/d$ can be positive or negative: if the beams have comparable fractional tunes in the range $0.15 \lesssim \nu \lesssim 0.85$, the magnitude of the effect, $|\Delta d/d|$, is at most 1.5%, which is negligible.

4.1 Tune values.

A positive value of $\Delta d/d$ indicates larger-than-nominal separation, which is favorable from the perspective of beam-beam dynamics. For all bunches, and for all PCs, $\Delta d/d$ is > 0 for $\nu \gtrsim 0.4$ and thus this is the favored range of tunes (assuming equal fractional tunes for the two beams). The crossing angle vanishes for $\nu \approx 0.35$, but it is not large for any reasonable value of the tune. Thus the dynamics favors the range of fractional tunes $\gtrsim 0.35$.

5 REFERENCES

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